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Electrodynamics of a flux transfer event: Experimental test of the Southwood model

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[1] On 12 September 1999, a conjunction between two SuperDARN radars and the Ørsted satellite gave, for the first time, simultaneous access to the ionospheric convection enhancement and the field-aligned currents (FACs) associated with a Flux Transfer Event. The radars observed an azimuthally elongated convection flow burst and the Ørsted satellite observed a series of successive small-scale parallel currents alternating between downward and upward. The most poleward pair of currents, whose directions were in agreement with the Southwood model, was observed when Ørsted crossed the front edge of the flow burst. A quantitative comparison of the current density of each FAC and of the Pedersen current density indicates that the closure current for this FACs pair occurred inside the flow burst, confirming the validity of the Southwood model. The Poynting flux carried by the parallel currents was less than 1% of the power carried by the solar wind plasma. **INDEX TERMS:** 2409 Ionosphere: Current systems (2708); 2431 Ionosphere: Ionosphere/magnetosphere interactions (2736); 2463 Ionosphere: Plasma convection; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions. **Citation:** Marchaudon, A., J.-C. Cerisier, R. A. Greenwald, and G. J. Sofko (2004), Electrodynamics of a flux transfer event: Experimental test of the Southwood model, *Geophys. Res. Lett.*, 31, L09809, doi:10.1029/2004GL019922.

1. Introduction

[2] Magnetopause reconnection is the main source of magnetospheric convection. Initially considered as a steady process by Dungey [1961], Haerendel *et al.* [1978] and Russell and Elphic [1978] discovered independently the intermittent and spatially limited nature of reconnection. Under the name of Flux Transfer Events (FTEs), Russell and Elphic [1978] first recognised the bipolar signature in the magnetic field component normal to the magnetopause as the main observational characteristic of bursts of magnetic reconnection. Later studies allowed refined descriptions of FTEs, namely the plasma signature inside the reconnected flux tube, consisting of a mixture of magnetosheath and magnetospheric plasma

[e.g., Farrugia *et al.*, 1988], the accelerated ion flows [e.g., Paschmann *et al.*, 1982] and their larger occurrence rate during periods of southward interplanetary magnetic field (IMF) [e.g., Berchem and Russell, 1984; Lockwood and Smith, 1992].

[3] Several models [Lee, 1986; Southwood, 1987] of the electrodynamics of FTEs have been proposed which describe the distribution of parallel currents inside the reconnected flux tube and closure Pedersen currents in the ionosphere. In the Lee [1986] model, a downward current flows all around the tube with an upward return current at the centre. In the Southwood [1987] model, parallel currents of opposite signs flow on the flanks of the flux tube, closed by a Pedersen current across the tube and perpendicular to the convection velocity.

[4] The reconnected flux tubes map along magnetic field lines into the ionosphere where radar and optical signatures can be observed. Using the STARE VHF coherent radar, Goertz *et al.* [1985] were the first to observe sporadic and spatially limited flow bursts which they related to magnetic merging at the magnetopause, as indicated by the simultaneous satellite observations. Several studies with the PACE HF radar followed. Pinnock *et al.* [1991, 1993] presented cases of enhanced convection channels superimposed on the continuous cusp echoes, with a larger extent in longitude than in latitude. Inside flow channels, the velocity was larger than in the ambient plasma and was directed mainly northward, as expected by the Southwood [1987] model for FTEs. During this period, optical observations were also made based on all-sky cameras and photometers showing bursts of precipitation generated in the auroral oval. These were also azimuthally elongated and moved poleward [Sandholt *et al.*, 1986, 1990].

[5] Experimentally, few studies of the electrodynamics of FTEs have been performed. Basinska *et al.* [1989] and Escoubet *et al.* [1992] used the Southwood [1987] model to interpret magnetic and electric fields data from low-altitude satellites in terms of FTEs. Several recent studies [Milan *et al.*, 2000; McWilliams *et al.*, 2001; Lockwood *et al.*, 2001] have associated convection flow bursts seen by HF radars with azimuthally elongated bands of auroral precipitation that were seen by satellite UV cameras and were interpreted as signatures of upward FACs located on one side of the flow burst.

[6] In this paper, we present the first direct measurement (by magnetometer) of the FAC system associated with a FTE in conjunction with the two-dimensional convection field of the associated flow burst. Taking into account the direction of motion of the flow burst, we show that the distribution of these FACs agrees with the Southwood [1987] model. Moreover, we verify that these FACs were closed in the ionosphere by the Pedersen current flowing

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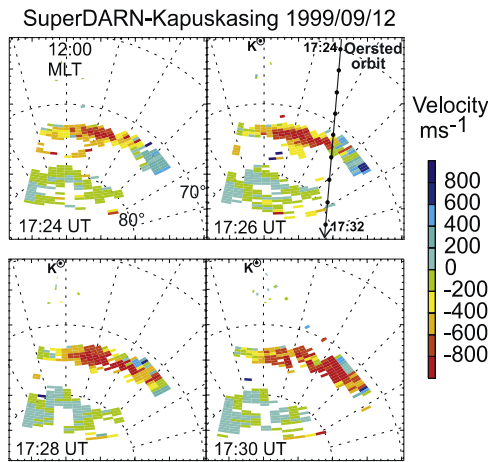


Figure 1. L-o-s velocity maps (magnetic coordinates) of the Kapuskasing (K) radar for the period 17:24–17:30 UT. Negative velocities represent motion away from the radar (colour-coded from yellow to red). The Ørsted orbit is superimposed on the 17:26 UT map (black dots are separated by one minute).

inside the flow burst. Finally, we estimate the power dissipated by Joule heating in the ionosphere and compare it with the power carried by the solar wind.

2. Instrumentation and Context

[7] The SuperDARN radars [Greenwald *et al.*, 1995] measure the line-of-sight (l-o-s) velocity of the ionospheric plasma in 16 adjacent beam directions separated by 3.3° in azimuth. A full scan, completed in 2 minutes, thus covers 53° in azimuth and over 3000 km in range with a resolution of 45 km. On 12 September 1999, between 17:00 and 18:00 UT, the common field-of-view of the Saskatoon and Kapuskasing radars was located in the 0900–1200 MLT sector. Both radars observed the eastern edge of the dawn convection cell, and the ionospheric footprint of the polar cusp with signatures characterised by a series of convection flow bursts moving westward. We will focus on one of these events observed between 17:22 and 17:32 UT.

[8] The Ørsted satellite, in a quasi-circular polar orbit at about 800 km altitude, is dedicated to measurements of the Earth's magnetic field. Magnetic field perturbations due to FACs are obtained by subtracting the IGRF model of the Earth's magnetic field. Assuming infinite current sheets, the orientation of the sheet and the FAC intensity can be deduced. Ørsted crossed the SuperDARN field-of-view from south to north between 0900 and 1000 MLT (around 17:28 UT) when the convection burst was observed close to the eastern edge of the dawn cell.

[9] The IMF and solar wind parameters were measured by the ACE satellite. The B_z component remained stable and negative at about -5 nT for one hour before the event, taking into account the approximate delay of 45 minutes to the dayside magnetopause. The B_y component, which was small and fluctuated around 0 nT, became slightly positive for the 10 minute period when the convection burst was observed. The solar wind pressure was initially high and

stable at 5 nPa up to 17:15 UT but decreased to 3.5 nPa between 17:15 and 17:30 UT during the event.

3. Observations

[10] Between 16:15 and 18:00 UT, the SuperDARN radars observed the usual ionospheric signature of the polar cusp, characterised by plasma entry into the polar cap in the northwestward direction. This direction is consistent with asymmetric convection cells, circular duskside and crescent-shaped dawnside, for positive IMF B_y . The Kapuskasing radar showed a series of convection bursts moving northwestward and probably triggered by magnetopause reconnection. These flow bursts were elongated in azimuth. In this study, we focus on the flow burst, starting at 17:22 UT which remained in the field of view of the radar for about 20 minutes and was sampled by the Ørsted satellite around 17:28 UT. The plasma velocity inside the flow burst was larger than 1000 m s^{-1} and exceeded the convective velocity in the surrounding plasma. The phase velocity of the flow burst (deduced from the slope of the velocity signature in the range-time plots from different radars beams) was of the same order, around 900 m s^{-1} . Figure 1 shows a selection of radial convection maps in magnetic latitude-magnetic local time (MLAT-MLT) coordinates for the Kapuskasing radar between 17:24 and 17:30 UT. Negative velocities (away from the radar) are colour-coded from yellow to red. The maps show clearly that the burst moved in the northwestward direction. An intensification of the convection inside the flow burst (velocities colour-coded in red) was observed after 17:26 UT. Velocity vectors deduced from combined Saskatoon and Kapuskasing data confirm the northwestward direction of the flow in the burst. The westernmost beams of the Kapuskasing radar showed southward and eastward velocities (positive velocities toward the radar, colour-coded in blue) adjacent to the flow burst. These velocities are attributed to sunward convection in the dawnside crescent-shaped convection cell.

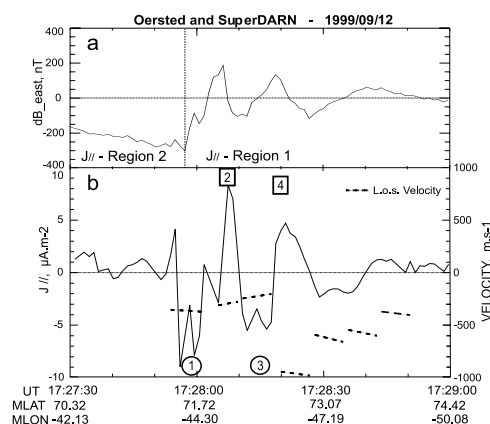


Figure 2. (a) Eastward magnetic perturbations deduced from the Ørsted data, with indication of the large-scale parallel current. (b) Field-aligned current densities averaged over 7 seconds (upward current is positive). The four small-scale current sheets are labelled (1) to (4) from south to north respectively. Dotted segments represent the l-o-s velocity interpolated from the three scans closest to the time of the Ørsted pass.

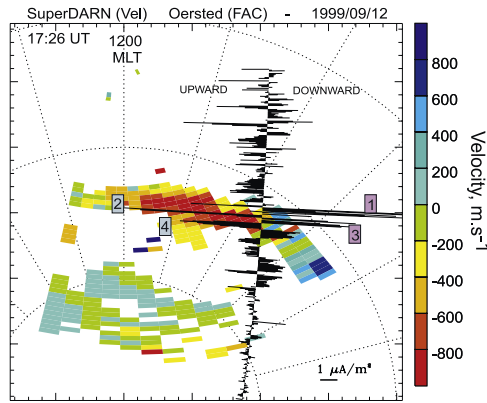


Figure 3. L-o-s velocity map (magnetic coordinates) of the Kapuskasing radar at 17:26 UT. The Ørsted orbit is superimposed on the map with the FAC intensities plotted perpendicular to the orbit. Labels (1) to (4) correspond to the four small-scale current sheets.

[11] Figure 2 displays the eastward (perpendicular to the magnetic meridian plane) component of the magnetic field perturbation and the parallel current observed by Ørsted. The eastward component showed large-scale variations associated with the usual Region-1 downward and Region-2 upward field-aligned current structure. The Region-0 current was not observed probably because the Ørsted trajectory is too far from noon, where this current is usually observed, thus confirming that Ørsted crossed the auroral oval on the dawnside of the polar cusp. Inside the Region-1 current, two large-amplitude oscillations were superimposed on the larger-scale variation of the eastward component of the magnetic perturbation and were associated with four small-scale and intense field-aligned current sheets, alternatively downward and upward. From south to north, these current sheets are labelled (1) to (4). Current (1) is downward with 45 km latitudinal extent and $-7 \mu\text{A m}^{-2}$ intensity; current (2) is upward with 10 km extent and $7 \mu\text{A m}^{-2}$ intensity; current (3) is downward with 40 km extent and $-4.5 \mu\text{A m}^{-2}$ intensity and current (4) is upward with 45 km extent and $4 \mu\text{A m}^{-2}$ intensity. The orientation of the current sheets varies between 10 and 30° from magnetic east, which is not far from the convection direction.

[12] Figure 3 shows the Ørsted trajectory and the FACs superimposed on the 17:26 UT Kapuskasing radial convection map. The length of the solid lines perpendicular to the orbit is proportional to the current intensity with upward (downward) currents plotted on the left- (right-) hand side of the figure. By interpolation between the 3 successive scans (17:24, 17:26 and 17:28 UT), closest to the time of the satellite pass, the radial convection velocity at the time of the Ørsted pass in each radar cell magnetically conjugate to the satellite was determined. This velocity is plotted together with the parallel current density on the bottom panel of Figure 2. The radial velocities are essentially equal to the convection velocity because the l-o-s directions were almost along the convection contours. The region of large convection velocities representing the flow burst is associated with the high-latitude pair of FACs labelled (3) and (4). The position of the pair of FACs (3) and (4) on each side of the

flux tube agrees with the model of *Southwood* [1987]. Furthermore, the upward current on the northern side and the downward current on the southern side are consistent with the northwestward motion of the flow burst.

[13] The low-latitude pair of FACs labelled (1) and (2) is located in the convection reversal (identified as the boundary between red-yellow and blue velocities) and thus not associated with the flow burst. The sign of FAC (1) agrees with the model of the superposition of global convection and large-scale FACs for positive B_y proposed by *Cowley et al.* [1991] and experimentally verified by *Lockwood et al.* [1993], *Milan et al.* [2000] and *McWilliams et al.* [2001]. However, the origin of FAC (2) remains unclear. Although a definitive explanation cannot be given from the available data set, several hypothesis can be put forward, including the failure of the infinite current sheet hypothesis, a freshly created FTE, or the effect of time variations of the large-scale convection in response to the IMF change.

4. Discussion and Summary

[14] In order to check quantitatively the consistency between the current pair and the motion of the flux tube, we have compared the densities of the FACs and of the ionospheric Pedersen current across the flux tube. We assume, for simplicity, as in the *Southwood* model, uniform ionospheric conductances, uniform plasma flow inside the flux tube and a vertical magnetic field. The convection velocity is mainly westward and the convection electric field (and the Pedersen current) is mainly northward. Thus, the excess Pedersen current across the tube diverges into FACs flowing on the flanks of the flux tube. In this model, the density of each FAC equals the Pedersen current flowing across the flux tube. In the frame of the ambient plasma, the Pedersen current density inside the flux tube is:

$$J_P = \Sigma_P E = \Sigma_P V B_{iono}.$$

Numerically, with $B_{iono} = 5 \times 10^4$ nT, with Pedersen conductance $\Sigma_P = 6$ S due to solar ionisation determined for the solar zenith angle at the time of observation from the empirical model of *Senior* [1991], and with $V = 750$ m s $^{-1}$ representing the excess plasma velocity inside the flux tube with respect to the ambient plasma, the Pedersen current density is $J_P = 0.225$ A m $^{-1}$. Because the flux tube is elongated along magnetic iso-latitudes, the intensity of the upward and downward currents feeding the Pedersen current are obtained by integrating separately the density of the parallel currents (3) and (4) along the magnetic meridian. Both amount to 0.18 A m $^{-1}$. The above evaluation shows that the density of each parallel current is approximately equal to the density of the Pedersen current, thus confirming that the system of FACs (3) and (4) is closed by the additional Pedersen current across the flux tube.

[15] From Figure 3, the transverse dimensions of the reconnected flux tube in the ionosphere are $l \times L = 100 \times 1000$ km. For the solar wind pressure P_{SW} of 5 nPa measured by ACE, the equilibrium total magnetic field at the subsolar magnetopause is 112 nT. From the conservation of magnetic flux between the magnetosphere and the ionosphere, the surface of the flux tube at the magnetopause

is $\sim 1 R_E^2$, in good agreement with observations [Saunders et al., 1984; Bosqued et al., 2001].

[16] It is also possible to estimate the power Π_P dissipated by the Pedersen current in the form of Joule heating, which is given by:

$$\Pi_P = \frac{J_P^2 l L}{\Sigma_P} = 8.4 \times 10^8 W.$$

Assuming no dissipation by the parallel currents, the Poynting flux at the magnetopause is $1.9 \times 10^{-5} W m^{-2}$, which is less than 1% of the available solar wind kinetic power $P_{SW} V_{SW} = 2.5 \times 10^{-3} W m^{-2}$, for the solar wind velocity $V_{SW} \approx 500 km s^{-1}$.

[17] In summary, we have reported the observation of two small-scale intense FACs of opposite signs located on each side of an ionospheric convection flow burst, typical of the ionospheric signature of a FTE. The sign of these FACs with respect to the direction of motion of the flow burst agrees with the Southwood [1987] model. Moreover, the current density of each FAC approximately equals the Pedersen current density inside the flow burst, showing that the two FACs and the Pedersen closure current belong to the same circuit. These results are the first direct observations of both the system of FACs associated with a FTE and the accompanying ionospheric flow burst structure. The results represent a clear experimental verification of the Southwood [1987] model.

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